Induction of Engineered Residual Stresses Fields and Enhancement of Fatigue Life of High Reliability Metallic Components by Laser Shock Processing

J.L. Ocaña, J.A. Porro, M. Díaz, L. Ruiz de Lara, C. Correa, A. Gil-Santos, D. Peral

Centro Láser UPM.
Universidad Politécnica de Madrid.
Campus Sur UPM. Ctra. de Valencia, km. 7.3. 28031 Madrid. SPAIN
email: jlocana@etsii.upm.es

Conference 8603
High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications II
Induction of Engineered Residual Stresses Fields and Enhancement of Fatigue Life of High Reliability Metallic Components by Laser Shock Processing

OUTLINE:

• Introduction
• Process Experimental Setup
  - Irradiation system
  - Experimental diagnosis system
• Experimental Procedure
• Experimental Results for Al2024-T351, Ti6Al4V and AISI 316L
  - Residual stresses
  - Tensile Strength
  - Fatigue Life
• Discussion and Outlook
  - Prospects for new technological applications of LSP
Laser Shock Processing (LSP) is being increasingly applied as a technique allowing the effective induction of residual stresses fields in metallic materials allowing a high degree of surface material protection against fatigue crack propagation, abrasive wear, chemical corrosion and other failure conditions, what makes the technique specially suitable and competitive with presently use techniques for the treatment of heavy duty components in the aeronautical, nuclear and automotive industries.

According to the inherent difficulty for the prediction of the shock waves generation (plasma) and evolution in treated materials, the practical implementation of LSP processes needs an effective predictive assessment capability coupled to a readily controllable experimental setup for a correct application of treatment parameters and an associate material properties characterization capability.

In the present communication, the practical LSP treatment and associate specimens characterization capabilities developed at CLUPM (Spain) are presented along with selected results obtained in several relevant aerospace and nuclear industry alloys.
REMINDER OF LSP PHYSICAL PRINCIPLES (1/2)

FREE MODE

CONFINED MODE

FREE PLASMA EXPANSION

IMPROVED PRESSURE AND IMPULSION

Confining Layer
Plasma/Vapour
Coating Layer
Bulk Material

Laser

Pressure pulse

Laser Pulse Intensity (W/cm²)
Pressure (GPa)
Time (s)

2–7 February 2013
The Moscone Center
San Francisco, California, USA

CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID

SPIE Photonics West
REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)
PROCESS EXPERIMENTAL SETUP
Spectra Physics Q-Switched Nd:YAG Laser

\[
\begin{align*}
\lambda &= 1064 \text{ nm} ; \ E = 2,5 \text{ J/pulse} \\
\lambda &= 532 \text{ nm} ; \ E = 1,4 \text{ J/pulse}
\end{align*}
\]

\[\tau = 10 \text{ ns} ; \ f = 10 \text{ Hz}\]
PROCESS EXPERIMENTAL SETUP

**LSP Treatment Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength (nm); Q-switched Nd:YAG</td>
<td>1064</td>
</tr>
<tr>
<td>Energy per pulse (J/pulse)</td>
<td>2.0</td>
</tr>
<tr>
<td>Pulse temporal width (ns)</td>
<td>≈ 9</td>
</tr>
<tr>
<td>Laser spot diameter (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Ratio x-y pitch</td>
<td>1</td>
</tr>
<tr>
<td>Confining medium</td>
<td>Water jet ≈ 2 bar</td>
</tr>
<tr>
<td>Absorbing coating overlay</td>
<td>No</td>
</tr>
</tbody>
</table>
PROCESS EXPERIMENTAL SETUP

CONCEPTUAL INTERRELATED DIAGNOSTICS SYSTEM

OSCILLOSCOPE
BEAM CONTROL

CALORIMETER
PHOTODiode

LASER

BEAM
SPLITTER

PLASMA

ICCD

HYDRODYNAMIC
ANALYSIS

PRESSURE
MEASUREMENT

INTERFEROMETER

FLASH

SPECTROGRAPH

OPTICAL
FIBER

LASER

SPECTRAL
ANALYSIS

PULSE GENERATOR

LASER
CONTROL

CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID

2-7 February 2013
The Moscone Center
San Francisco, California, USA

SPIE Photonics West
CONCEPTUAL INTERRELATED DIAGNOSTICS SYSTEM
PROCESS EXPERIMENTAL SETUP

IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY
PROCESS EXPERIMENTAL SETUP

IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY

EMISSION SPECTROSCOPY

Spectroscopic system calibrated in wavelength with Hg lamp and in intensity with Deuterium lamp
Electron density determination via Stark effect of Al II line at 2816.2 nm:

<table>
<thead>
<tr>
<th>Distance from target</th>
<th>2 µs</th>
<th>3 µs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>20.4 $10^{16}$ cm$^{-3}$</td>
<td>2.4 $10^{16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>6 mm</td>
<td>17.2 $10^{16}$ cm$^{-3}$</td>
<td>2.0 $10^{16}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>
Electron temperature determination through Boltzmann plot of relative intensities of Mg II lines at 279.5528 nm, 280.2704 nm, 292.8633 nm and 293.6509 nm:

Preliminary electron temperature distributions in the range of 1.0-1.5 eV (i.e. ≈ 11 600 - 17 400 K) were found close to the target 2-3 μs after laser shut-down.
EXPERIMENTAL PROCEDURE
Experimental Procedure

Equivalent Overlapping g = EOD = \( \frac{N^o \text{ of pulses}}{\text{Total treated surface}} \) = \( \frac{x \ y}{\Delta x \ \Delta y} \) = \( \frac{x \ y}{\Delta s} \) = \( \frac{x \ y}{d \ d} \) = \( \frac{1}{d^2} \)

Equivalent Energy Density = EED = \( \frac{N^o \text{ of pulses} \cdot \text{Pulse Energy}}{\text{Total treated surface}} \) = \( \frac{x \ y}{\Delta x \ \Delta y} \) E = \( \frac{x \ y}{d \ d} \) E = \( \frac{E}{d^2} \)

Equivalent local overlapping factor = ELOF = \( \frac{N^o \text{ of pulses} \cdot \text{Pulse Area}}{\text{Total treated surface}} \) = \( \frac{\pi \ \phi^2}{4 \ d^2} \) = \( \frac{\pi \left( \phi \right)^2}{4 \ d} \)
EXPERIMENTAL PROCEDURE

Table I: Relation between overlapping pitch and equivalent number of pulses per unit surface corresponding to the defined sweeping procedure.

<table>
<thead>
<tr>
<th>Overlapping pitch Y (mm)</th>
<th>Equivalent overlapping density (pulses/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.588</td>
<td>289</td>
</tr>
<tr>
<td>0.33</td>
<td>900</td>
</tr>
<tr>
<td>0.285</td>
<td>1225</td>
</tr>
<tr>
<td>0.2</td>
<td>2500</td>
</tr>
<tr>
<td>0.141</td>
<td>5000</td>
</tr>
</tbody>
</table>
**Material:** Al2024 T3

**Pulses:** $\phi=1,5 \text{ mm;} \quad \tau=10 \text{ ns;} \quad f=10 \text{ Hz;}$

$E=1 \text{ J/pulse;} \quad I=1,41 \text{ GW/cm}^2$

**Swept Area:** $15x15 \text{ mm}^2; \quad 2500 \text{ pulses/cm}^2$
## EXPERIMENTAL RESULTS

### Reported Analysis

<table>
<thead>
<tr>
<th>Pulse Density (pulses/cm²)</th>
<th>Al2024-T351 30x20x8 mm³</th>
<th>Ti6Al4V 30x20x10 mm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td><img src="image-1.png" alt="Image 1" /></td>
<td><img src="image-2.png" alt="Image 2" /></td>
</tr>
<tr>
<td>1600</td>
<td><img src="image-3.png" alt="Image 3" /></td>
<td><img src="image-4.png" alt="Image 4" /></td>
</tr>
<tr>
<td>2500</td>
<td><img src="image-5.png" alt="Image 5" /></td>
<td><img src="image-6.png" alt="Image 6" /></td>
</tr>
<tr>
<td>5000</td>
<td><img src="image-7.png" alt="Image 7" /></td>
<td><img src="image-8.png" alt="Image 8" /></td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

Surface Roughness (Topographic Confocal microscopy): Al2024-T351

<table>
<thead>
<tr>
<th></th>
<th>No treatment</th>
<th>900 pulses/cm²</th>
<th>1600 pulses/cm²</th>
<th>2500 pulses/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa (µm)</td>
<td>7.96</td>
<td>5.23</td>
<td>4.82</td>
<td>4.96</td>
</tr>
<tr>
<td>&lt;Δz&gt;</td>
<td>----</td>
<td>10.30</td>
<td>20.00</td>
<td>26.82</td>
</tr>
</tbody>
</table>
Surface Roughness (Topographic Confocal microscopy): Ti6Al4V

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No treatment</th>
<th>900 pulses/cm²</th>
<th>1600 pulses/cm²</th>
<th>2500 pulses/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa (µm)</td>
<td>9.98</td>
<td>3.62</td>
<td>3.87</td>
<td>3.87</td>
</tr>
<tr>
<td>&lt;Δz&gt;</td>
<td>----</td>
<td>2.81</td>
<td>7.40</td>
<td>5.80</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

Microhardness (HV)

Slight increase in microhardness in Al2024-T351
Higher for higher LSP treatment intensity

No apparent hardening effect in Ti6Al4V.
EXPERIMENTAL RESULTS

Wear resistance (According to ASTM G99-04)

Al2024-T351

Slight wear improvement in Al2024-T351 at low loads

Considerable wear improvement in Al2024-T351 at moderate loads
Wear resistance (According to ASTM G99-04)

Ti6Al4V

Slight negative wear impact in Ti6Al4V at low loads

Inappreciable wear improvement in Ti6Al4V at moderate loads
EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)
Residual Stresses (According to ASTM E837-08)

**Al2024-T351**

Relatively broad difference between $S_{\text{max}}$ and $S_{\text{min}}$ in Al2024-T351

**Ti6Al4V**

Relatively small difference between $S_{\text{max}}$ and $S_{\text{min}}$ in Ti6Al4V
Residual Stresses (According to ASTM E837-08)

**S\text{max}** in Al2024-T351 for different irradiation intensities

**S\text{max}** in Ti6Al4V for different irradiation intensities
Residual Stresses (According to ASTM E837-08)

Ti6Al4V: Comparison LSP-Shot Peening

Substantial improvement in Residual Stresses Field in Ti6Al4V vs. to Shot Peening

Decisive improvement in protected depth reached in Ti6Al4V for different irradiation intensities
Residual Stresses Permanence upon Thermal Treatment

AISI 316L Steel

S\text{max} permanence in AISI 316L Steel after different Thermal Treatment Temperatures for a 900 pulses/cm\textsuperscript{2} LSP Treatment Intensity

S\text{max} permanence in AISI 316L Steel after different Thermal Treatment Temperatures for a 1600 pulses/cm\textsuperscript{2} LSP Treatment Intensity
EXPERIMENTAL RESULTS

Process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1064</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>10</td>
</tr>
<tr>
<td>Energy (J/pulse)</td>
<td>2.8</td>
</tr>
<tr>
<td>Pulse width (ns)</td>
<td>~ 9</td>
</tr>
<tr>
<td>Spot diameter (mm)</td>
<td>~ 1.5</td>
</tr>
<tr>
<td>Overlapping (pulses/cm²)</td>
<td>900</td>
</tr>
<tr>
<td>Overlapping (pulses/cm²)</td>
<td>1600</td>
</tr>
<tr>
<td>Confining medium</td>
<td>Water jet</td>
</tr>
<tr>
<td>Absorbent coating</td>
<td>No</td>
</tr>
</tbody>
</table>

LSP Experimental setup at CLUPM

900 pul/cm² 1600 pul/cm²

900 pulses/cm² 1600 pulses/cm²

900 pulses/cm² + Heat treat.: 500 °C, 8h
Residual Stresses:

AISI 316L Stainless steel, $\lambda = 1064 \text{ nm}$
2.8 J/pulse, Spot diameter = 1.5 mm, Water jet, without paint

- $S_{\text{max}}, 900 \text{ pulses/cm}^2$
- $S_{\text{min}}, 900 \text{ pulses/cm}^2$
- $S_{\text{max}}, 1600 \text{ pulses/cm}^2$
- $S_{\text{min}}, 1600 \text{ pulses/cm}^2$
EXPERIMENTAL RESULTS

“Sub-size” Tensile Specimen
ASTM E 8M

“Bone” Fatigue Specimen
ASTM E 466
EXPERIMENTAL RESULTS

Tensile Tests:

<table>
<thead>
<tr>
<th>Property</th>
<th>Base material</th>
<th>LSP 900</th>
<th>LSP 1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Modulus (GPa)</td>
<td>177.205</td>
<td>182.099</td>
<td>185.446</td>
</tr>
<tr>
<td>Engineering elastic limit (MPa)</td>
<td>355.410</td>
<td>356.390</td>
<td>359.930</td>
</tr>
<tr>
<td>Maximum tensile stress (MPa)</td>
<td>633.608</td>
<td>629.700</td>
<td>626.870</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

Fatigue Tests:

<table>
<thead>
<tr>
<th>S_a (Mpa)</th>
<th>S_max (Mpa)</th>
<th>F_max (kN)</th>
<th>F_mean (kN)</th>
<th>Cycles 900</th>
<th>Cycles 1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>622</td>
<td>54.507</td>
<td>29.979</td>
<td>35574</td>
<td>60199</td>
</tr>
<tr>
<td>260</td>
<td>578</td>
<td>50.613</td>
<td>27.837</td>
<td>57777</td>
<td>75105</td>
</tr>
<tr>
<td>240</td>
<td>533</td>
<td>46.720</td>
<td>25.696</td>
<td>91471</td>
<td>107098</td>
</tr>
<tr>
<td>230</td>
<td>511</td>
<td>44.773</td>
<td>24.625</td>
<td>130302</td>
<td>165560</td>
</tr>
<tr>
<td>220</td>
<td>489</td>
<td>42.827</td>
<td>23.555</td>
<td>233301</td>
<td>185802</td>
</tr>
<tr>
<td>210</td>
<td>467</td>
<td>40.880</td>
<td>22.484</td>
<td>268180</td>
<td>444006</td>
</tr>
<tr>
<td>200</td>
<td>444</td>
<td>38.933</td>
<td>21.413</td>
<td>1000000</td>
<td>1000000</td>
</tr>
</tbody>
</table>

LogN=16.33764-4.79302LogS_a  \( R^2=0.99760 \)

LogN=22.51020-7.35620LogS_a  \( R^2=0.98967 \)

LogN=21.09071-0.01178S_a  \( R^2=0.87937 \)
EXPERIMENTAL RESULTS

Fatigue Tests:

<table>
<thead>
<tr>
<th>$S_a$ (Mpa)</th>
<th>$S_{Max}$ (Mpa)</th>
<th>$F_{max}$ (kN)</th>
<th>$F_{mean}$ (kN)</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>622</td>
<td>54.507</td>
<td>29.979</td>
<td>6000</td>
</tr>
<tr>
<td>230</td>
<td>511</td>
<td>44.773</td>
<td>24.625</td>
<td>128632</td>
</tr>
<tr>
<td>200</td>
<td>444</td>
<td>38.933</td>
<td>21.413</td>
<td>259987</td>
</tr>
<tr>
<td>180</td>
<td>400</td>
<td>35.040</td>
<td>19.272</td>
<td>1000000</td>
</tr>
</tbody>
</table>

Log $N = 16.33764 - 4.79302 \log S_a$
$R^2 = 0.99760$

Log $N = 17.00022 - 5.03482 \log S_a$
$R^2 = 0.99$

Log $N = 22.51020 - 7.35620 \log S_a$
$R^2 = 0.98967$

Base Material
LSP 900
LSP 900 + Heat treatment (500ºC; 8h)

CENTRO LÁSER
 UNIVERSIDAD POLITÉCNICA DE MADRID

2–7 February 2013
 The Moscone Center
 San Francisco, California, USA

SPIE Photonics West
EXPERIMENTAL RESULTS


\[ \frac{da}{dN} = C.K^m \]

<table>
<thead>
<tr>
<th>Pulse density (cm(^{-2}))</th>
<th>C (mm/cycle)</th>
<th>M (dimensionless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (No LSP treatment)</td>
<td>4x10(^{-13})</td>
<td>7.664</td>
</tr>
<tr>
<td>900</td>
<td>8x10(^{-13})</td>
<td>6.818</td>
</tr>
<tr>
<td>1350</td>
<td>2x10(^{-11})</td>
<td>5.733</td>
</tr>
<tr>
<td>2500</td>
<td>3x10(^{-10})</td>
<td>4.723</td>
</tr>
</tbody>
</table>
DISCUSSION AND OUTLOOK

A typical prospective LSP application to welding technology

Fig. 4. Dimensions of the tensile specimen.
DISCUSSION AND OUTLOOK

Fig. 10. (a) Tensile properties at different regions of the weld (b) Strain fields in the x-direction for the specimen before failure.

Fig. 11. Residual stresses for the various peened FSW specimens.

Fig. 12. Two-dimensional map of the measured residual stress for the unpeened FSW specimen.

Fig. 13. Two-dimensional map of the measured residual stress for the shot peened FSW specimen.

Fig. 14. Two-dimensional map of the measured residual stress for the laser peened FSW specimen.

With the aid of the experimental irradiation and process diagnosis system implemented at CLUPM (Spain), a complete feasibility of the LSP technique at laboratory scale for the induction of improved material surface properties has been accomplished. The implementation of the appropriate experimental diagnosis methods enables a reliable process predictive assessment capability in view of process industrial implementation.

The need for a practical capability of LSP process control in practical applications has led to the joint development of comprehensive theoretical/computational models and related material properties characterization capabilities able to properly assess the complex material issues arising in the process.

With the aid of the developed experimental testing capability, a specifically targeted analysis of LSP induced effects (such as surface morphology, surface composition transformations, surface mechanical behaviour, deep residual stress fields and others) is made possible, thus allowing a practical development of the technique from an industrial point of view.

Representative applications of the LSP technique to the treatment of typical aeronautic grade alloys (typically Al and Ti) and stainless steels characteristic of the aerospace, nuclear, biomedical and equipment industries, as well as to the post-treatment of welded metallic joints have been successfully conducted to the induction of compressive residual stresses fields decisively improving their fatigue life.

Taking into account the benefits on the life extension side and the prospects for substitution of competing environmentally aggressive technologies, LSP is to be considered as a sustainability enabling technique.
DISCUSSION AND OUTLOOK

EXPERIMENTAL CHARACTERIZATION OF MATERIAL PROPERTIES

LASER PLASMA INTERACTION SIMULATION AND DIAGNOSIS

NUMERICAL SIMULATION OF SOLID BEHAVIOUR
ACKNOWLEDGEMENTS

Work supported by MEC/MCINN (Spain; Projects DPI2005-09152-C02-01; MAT2008-02704/MAT; MAT2012-37782), UPM (Spain, Project CM CCG07-UPM/MAT-1964) and EADS-CASA (Spain)

REFERENCES

DISCUSSION AND OUTLOOK

LSP: An emerging industrial technology
LSP: An Emerging Sustainability Supporting Technology

Next event on LSP:

4th International Conference on Laser Peening and Related Phenomena

May 6th-10th 2013
ETS de Ingenieros Industriales, Universidad Politécnica de Madrid, SPAIN

Contact: jlocana@etsii.upm.es
http://www.upmlaser.upm.es/4-ICLPRP
Thank you very much for your attention!

jlocana@etsii.upm.es
Centro Láser U.P.M.
Campus Sur U.P.M.
Edificio Tecnológico "La Arboleda"
Carretera de Valencia km. 7,300
28031 Madrid - SPAIN
Tel. : (+34) 91 336 30 99
Fax.: (+34) 91 336 55 34
Email: claser@etsii.upm.es
jlocana@etsii.upm.es
Major Facilities (1/4)
Major Facilities (3/4)
Major Facilities (4/4)
The SHOCKLAS Calculational System